DMT Optimal On-Demand Relaying for Mesh Networks

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***Abstract*— This paper presents a new cooperative MAC (Medium Access Control) protocol called BRIAF (Best Relay based Incremental Amplify-and-Forward). The proposed protocol presents two features: on-demand relaying and selection of the best relay terminal. "On-demand relaying" means that a cooperative transmission is implemented between a source terminal and a destination terminal only when the destination terminal fails in decoding the data transmitted by the source terminal. This feature maximizes the spatial multiplexing gain r of the transmission. "Selection of the best relay terminal" means that a selection of the best relay among a set of (m-1) relay candidates is implemented when a cooperative transmission is needed. This feature maximizes the diversity order $d(r)$ of the transmission. Hence, an optimal DMT (Diversity Multiplexing Tradeoff) curve is achieved with a diversity order $d(r) = m(1-r)$ for $0 \le r \le 1$.**

I. INTRODUCTION

MULTIPLE input multiple output (MIMO) techniques are an important means to improve the performance of wireless systems in terms of spatial diversity. However, these techniques cannot be used in all wireless systems due to implementation issues (size of wireless terminals, space between antennas, and wavelength of the system). In this context, cooperative communications provide an interesting alternative for those wireless systems that cannot support multiple antenna terminals.

In a cooperative scenario, a source terminal S sends data to a destination terminal D. One or several relay terminals help the transmission by receiving the signal transmitted by S and forwarding the signal toward D (see Fig. 1).

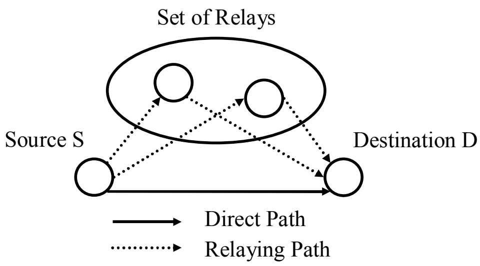

Fig. 1. Cooperation scenario with two relay terminals.

The two majors forwarding schemes used in cooperative protocols are Amplify-and-Forward (AF) and Selective Relaying (SR). In AF scenarios [1], relay terminals are non-regenerative. At the relay terminals, the received signal from S is simply amplified and forwarded toward D. In SR scenarios, relay terminals are regenerative. At a relay terminal T, the received signal from S is decoded and forwarded toward D when the quality of the S-T channel is good enough [2].

Spatial diversity is the main advantage provided by cooperative transmissions whereas their main limitation lies in the additional bandwidth consumption needed for relay terminal transmissions. Several cooperation techniques have been proposed in order to both maximize the spatial diversity and minimize the bandwidth consumption. To compare the proposed techniques, performance is described in terms of Diversity-Multiplexing Tradeoff (DMT). This criterion has been first developed in the context of MIMO techniques [3]. The DMT analysis of a transmission scheme yields the diversity gain $d(r)$ achievable for a spatial multiplexing gain r. A transmission scheme is said to have a spatial multiplexing gain r and a diversity gain $d(r)$ if the spectral efficiency R scales like $r\log_2 SNR$, and the outage probability decays like $1/SNR^{d(r)}$, where SNR is the signal-to-noise ratio at the destination D. In the context of cooperative transmissions, the spatial multiplexing gain r can be thought as the spectral efficiency of the cooperative transmission, normalized by the spectral efficiency of a direct transmission.

When a single relay terminal is involved in a cooperative scenario, an optimal DMT curve can be obtained using on-demand relaying [2]. In an on-demand relaying scenario, the relay terminal is transmitting only when D fails in decoding the data transmitted by S. So D is asking for cooperation with a signaling frame. The DMT curve is $d(r) = 2(1-r)$ for $0 \le r \le 1$ (see Fig. 2). The DMT is optimal but the diversity gain is limited to a factor of two. Note that optimal DMT curves can also be computed when no feedback information is provided by the destination terminal [4]. To increase the diversity gain, multiple relay terminals must be used. When (m-1) relay terminals are involved in a cooperative scenario, a diversity order of m can be achieved [5]. The relay terminals that have successfully decoded the data from S are transmitting a copy of the data frame toward D. From a coding point of view, this scenario implements a repetition scheme. The DMT curve becomes $d(r) = m(1-mr)$ for $0 \le r \le 1/m$. The improvement of the diversity gain is counterbalanced by increased bandwidth consumption due to the multiple relay transmissions. This approach has been improved using space-time coding (STC) [5]. The DMT curve is then $d(r) = m(1-2r)$ for $0 \le r \le 1/2$. Here also, the DMT is not optimal since the multiplexing gain r does not reached its optimal value of one. Moreover, the implementation of such a technique involves the transmission of many signaling frames in order to allocate a space-time code to each participating relay terminal. This bandwidth consumption is not taken into account in DMT analysis. This approach has been improved in [6]. The solution is based on the selection of the best relay among a set of (m-1) relay candidates. The DMT curve is also $d(r) = m(1-2r)$ for $0 \le r \le 1/2$ but, in that scenario, less resources are needed to implement the solution. However, the spatial multiplexing gain r is still limited by a factor of 1/2. Moreover, this protocol is always providing a "best relay" as long as there are terminals in the range of terminals S and D. A selection is done even when the selected relay terminal cannot improve the transmission performance between terminals S and D.

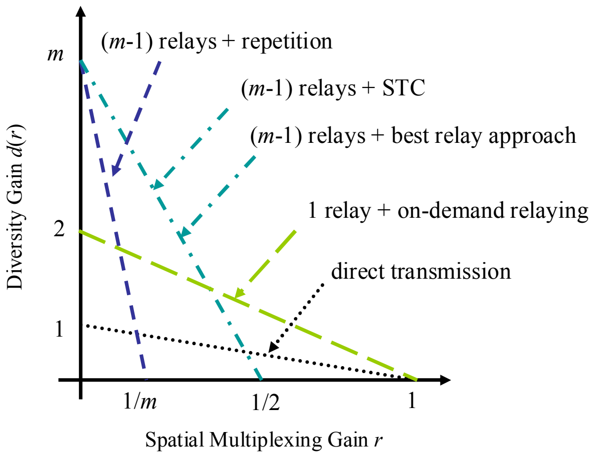

Fig. 2. DMT curves for several cooperation schemes.

The proposed protocol aims at providing a diversity gain of m while achieving a spatial multiplexing gain of one. This new cooperative protocol, called BRIAF (Best-Relay based Incremental Amplify-and-Forward), is based on the IEEE 802.11 standard for wireless networks and exhibits the following features: on-demand cooperation and selection of the best relay terminal. Cooperation is activated only when needed, i.e. only when the destination terminal D fails in decoding the data transmitted by the source terminal S. This feature allows maximization of the spatial multiplexing gain r. Moreover, when a cooperative communication is necessary, only the best relay terminal participates in the communication. This approach allows the maximization of the diversity gain $d(r)$. Hence, an optimal DMT can be achieved. The BRIAF protocol also implements two steps to select the best relay terminal. The first step selects the relay candidates that can efficiently improve the direct transmission. The second step evaluates each relay candidate and chooses the one that exhibits the best end-to-end channel gain. This approach prevents inefficient relay terminals from cooperating.

In Section II, we describe in detail the BRIAF protocol and section III presents the DMT analysis of the protocol. Simulation results are presented in section IV and we conclude in section V.

II. Description of the BRIAF Protocol

A. System Model

We consider a slow Rayleigh fading channel model following [2]. Our analysis focuses on the case of slow fading, to capture scenarios in which delay constraints are on the order of the channel coherence time. A half duplex constraint is imposed across each relay terminal, i.e. it cannot transmit and listen simultaneously. Let h_{ij} be the channel gain between a transmitting terminal i and a receiving terminal j. The channel gain h_{ij} captures the effects of path-loss, shadowing, and Rayleigh fading. We consider scenarios in which each fading coefficient h_{ij} is accurately measured by the receiver j, but not known to the transmitter i. We also assume that the channel gain h_{ij} is identical to the channel gain h_{ji}. This assumption is relevant since both channels are using the same frequency band. Statistically, channel gains h_{ij} are modeled as i.i.d circularly symmetric complex Gaussian random variables with zero mean and equal variance σ^2. Let P be the power transmitted by each terminal and σ_w^2 be the variance of the AWGN (Additive White Gaussian Noise) in the wireless channel. We define $SNR = P/\sigma_w^2$ to be the effective signal-to-noise ratio.

B. Protocol Description

The design of cooperative MAC (Medium Access Control) protocols in the context of IEEE 802.11-based networks ([7]-[12]) involves four main tasks: activation of the cooperative transmission mode, collection of cooperation information (CoI), relay selection, and notification to the terminals [13]. In the following, we review these tasks according to our proposal.

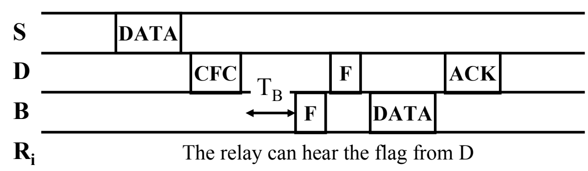

Fig. 3. Frame exchange sequence in the BRIAF protocol (S is the source terminal, D is the destination terminal, B is the best relay terminal, and R_i is a relay candidate)

The protocol begins with the transmission of the DATA frame from S. When the source terminal S sends its DATA frame, S transmits a signal. This signal is received, sampled, and stored at each terminal in the range of terminal S. The source message is then decoded. When the destination terminal D succeeds in decoding the DATA frame, terminal D sends an acknowledgment frame (ACK). When the terminals that have overheard the DATA frame from S, successfully decode the ACK frame, they discard the stored signal samples. When the destination terminal D fails in decoding the DATA frame, terminal D sends a short signaling frame CFC (Call For Cooperation) whenever it requires the terminals in its neighborhood to cooperate [8]. Terminal in the range of D that have not received the DATA frame from S, just ignore this signaling frame. Note that when the CFC frame is lost, the protocol enters a classical error recovery scenario. Hence, a cooperative scenario is activated at terminal T if two conditions are satisfied:

(1) Terminal T has successfully decoded both the DATA frame from S and the CFC frame from D.
(2) The cooperative transmission can improve the spectral efficiency of the direct transmission

$$I_{AF} > R/2 \quad (1)$$

$$I_{AF} = \frac{1}{2}\log_2\left[1 + SNR|h_{SD}|^2 + f\left(SNR|h_{ST}|^2, SNR|h_{TD}|^2\right)\right] \quad (2)$$

$$f(x,y) = xy/(x+y+1) \quad (3)$$

where I_{AF} is the mutual information of the relayed transmission using AF cooperation scheme. Equation (1) suggests that terminal T should participate in the cooperation if the observed capacity of a cooperative channel using the AF method is greater than the spectral efficiency *R/2*. Note that the spectral efficiency of the cooperative transmission is automatically decreased by a factor of 1/2 compared to the spectral efficiency of the direct transmission. This is due to the transmission of the best relay terminal.

Terminal T uses the DATA frame (resp. the CFC frame) to estimate the channel gain h_{ST} (resp. h_{TD}). Moreover, we enhance the CFC frame to facilitate signaling among the cooperative terminals. In the CFC frame, the destination specifies the target spectral efficiency *R* for data transmission and piggybacks the signal-to-noise ratio of the received DATA frame: $|h_{SD}|^2 SNR$. Hence, (1) can be computed at terminal T.

This selection of the relay candidates provides energy savings because terminals in the neighborhood of terminals S and D do not need to spend resources transmitting data that could not be exploited by D.

We assume that (m-1) terminals have been pre-selected ($m \geq 1$). As soon as a pre-selected terminal R_i, $1 \leq i \leq (m-1)$, receives the CFC frame from terminal D, terminal R_i triggers a timer $T_i = \lambda / h_i$ according to a channel quality measure h_i:

$$h_i = \min\left(\left|h_{SR_i}\right|^2, \left|h_{R_iD}\right|^2\right)$$

The best relay is denoted terminal B and is the terminal such that $T_B = \min\{T_1, T_2, \cdots, T_{(m-1)}\}$. The best relay has its timer reduced to zero first. Parameter λ can be tuned for different purposes. Increasing λ reduces the probability of collision to zero. Besides, increasing λ also increases the expected time needed for the network to find out the best relay. Therefore, there is a tradeoff between probability of collision and speed of relay selection. Adjusting parameter λ is beyond the scope of this study. More details on tuning λ can be found in [6].

The timer T_B of the best relay will expire first. At the best relay terminal B, the notification step consists in transmitting a short duration signaling frame to warn its neighborhood. All the relay candidates, while waiting for their timer to reduce to zero, are in listening mode. As soon as they hear another relay to flag its presence or forward information, they back off. The destination terminal D also forwards the flag frame to warn the relay candidates that are not in the range of the best relay terminal B. Then, the best relay terminal B sends a copy of the stored signal samples using the AF forwarding scheme and the destination terminal D decodes the data frame with the received signal samples. The decoding step may involve terminal S transmission. At the signal level, terminal D can combine the received signal from B and the received signal from S using a maximum ratio combining receiver. At the bit level, terminal D can combine the bit stream received from B and the bit stream received from S using a code combining technique [14]. When D succeeds in decoding the data frame, D sends an acknowledgment frame (ACK). Otherwise, D remains silent and triggers a classical error recovery mechanism. Note that if the set of relay candidates is empty, the protocol also triggers an error recovery mechanism.

III. DMT Analysis of the Protocol

We characterize our channel models using the system model described in the previous section, and a time-division notation; frequency-division counterparts to this model are straightforward. We use a base-band-equivalent, discrete-time channel model for the continuous-time channel. Three discrete time received signals are defined in the following. Here, $y_{ij}(n)$ denotes the signal received by terminal j and transmitted by terminal i. During a first time-slot, D and the best relay terminal B are receiving signals from S:

$$y_{SD}(n) = h_{SD}x(n) + w_{SD}(n)$$
$$y_{SB}(n) = h_{SB}x(n) + w_{SB}(n)$$

for $n = 1, 2, \cdots, T_M/2$, where T_M denotes the duration of time-slots reserved for each message.

When terminal D succeeds in decoding the data frame from S, no signal is transmitted by the best relay terminal B. Otherwise, the relay terminal sends a new signal using an AF cooperation scheme

$$y_{BD}(n) = h_{BD}[\beta y_{SB}(n)] + w_{BD}(n)$$

for $n = T_M/2 + 1, \cdots, T_M$. The noise $w_{ij}(n)$ between transmitting terminal i and receiving terminal j are all assumed to be i.i.d. circularly symmetric complex Gaussian with zero mean and variance σ_w^2. Symbols transmitted by the source terminal S are denoted $x(n)$. For simplicity, we impose the same power constraint at both the source and the relay: $E\left[|x(n)|^2\right] \leq P$ and $E\left[|\beta y_{SB}(n)|^2\right] \leq P$. Since we implement an AF cooperation scheme, the normalization factor β must satisfy $\beta^2 = P/\left(|h_{SB}|^2 P + \sigma_w^2\right)$. We assume that the source and the relay each transmit orthogonally on half of the time-slots. We also consider that a perfect synchronization is provided at the block, carrier, and symbol level.

To develop the DMT curve of the BRIAF protocol, we define the multiplexing gain r and the diversity order $d(r)$ by

$$\lim_{SNR\to+\infty} \frac{R}{\log_2(SNR)} = r$$

$$\lim_{SNR\to+\infty} -\frac{\log p_{BRIAF}^{out}(SNR,r)}{\log(SNR)} = d(r)$$

The probability $p_{BRIAF}^{out}(SNR,r)$ is the outage probability for a signal to noise ratio SNR and a spatial multiplexing gain r. So, for large SNR values, the spectral efficiency R of the transmission (in b/s/Hz) is

$$R = r\log_2 SNR$$

The outage probability $p_{BRIAF}^{out}(SNR,r)$ is given by

$$p_{BRIAF}^{out}(SNR,r) = \Pr[I_{BRIAF} \le R]$$

where I_{BRIAF} denotes the mutual information of the BRIAF protocol. The BRIAF protocol operates at spectral efficiency R when the direct transmission is successful, and operates at spectral efficiency $R/2$ when the best relay terminal B must amplify and forward the message it received. For given values of SNR and R, the outage probability $p_{BRIAF}^{out}(SNR,r)$ is defined by

$$\begin{aligned} p_{BRIAF}^{out}(SNR,r) &= \Pr[I_{BRIAF} \le R] \\ &= \Pr[I_D \le R]\Pr[I_{AF} \le R/2 | I_D \le R] \quad (4) \\ &= \Pr[I_{AF} \le R/2] \end{aligned}$$

where I_D is given by

$$I_D = \log_2\left(1 + SNR|h_{SD}|^2\right) \quad (5)$$

and I_{AF} is given in (2). The third equality in (4) follows from the fact that the event $[I_D \le R]$ is included in the event $[I_{AF} \le R/2]$ (see (2) and (5)). Using the definition of I_{AF}, we have that

$$p_{BRIAF}^{out}(SNR,r) = \Pr\left[1 + SNR|h_{SD}|^2 + f\left(SNR|h_{SB}|^2, SNR|h_{BD}|^2\right) \le SNR^r\right]$$

For large SNR values, we have that

$$p_{BRIAF}^{out}(SNR,r) \le \Pr\left[SNR|h_{SD}|^2 + f\left(SNR|h_{SB}|^2, SNR|h_{BD}|^2\right) \le SNR^r\right]$$

Let $A = SNR|h_{SD}|^2$, $B = f\left(SNR|h_{SB}|^2, SNR|h_{BD}|^2\right)$, and $C = SNR^r$. The event $[A + B \le C]$ can also be expressed as $[A \le C - B] \cap [B \le C - A]$. This event is included is the event $[A \le C] \cap [B \le C]$. So, for large values of SNR, we have that

$$p_{BRIAF}^{out}(SNR,r) \le \Pr\left[|h_{SD}|^2 \le SNR^{r-1}, f\left(SNR|h_{SB}|^2, SNR|h_{BD}|^2\right) \le SNR^r\right]$$

We split the right side of the above expression in two terms and study these two terms for high SNR values. From Lemma 2 in [6], we have that

$$\lim_{SNR\to+\infty} \frac{\log\left\{\Pr\left[|h_{SD}|^2 \le SNR^{r-1}\right]\right\}}{\log SNR} = r - 1 \quad (6)$$

because $|h_{SD}|^2$ is an exponential random variable with parameter σ^2. For the second term, we first adapt the result of Lemma 4 in [6]

$$\Pr\left[f(\rho a, \rho b) \le \rho^r\right] \le \Pr\left[\min(a,b) \le \rho^{r-1} + \sqrt{\rho^{r-2}\left(\rho^r + 1\right)}\right]$$

where $f(x,y)$ is defined in (3). Thus, we have that

$$\begin{aligned} &\Pr\left[f\left(SNR|h_{SB}|^2, SNR|h_{BD}|^2\right) \le SNR^r\right] \\ &\quad \le \Pr\left[\min\left(|h_{SB}|^2, |h_{BD}|^2\right) \le SNR^{r-1} + \sqrt{SNR^{r-2}\left(SNR^r + 1\right)}\right] \end{aligned}$$

The random variable $\min(|h_{SB}|^2,|h_{BD}|^2)$ is an exponential variable with parameter $2\sigma^2$ because $|h_{SB}|^2$ and $|h_{BD}|^2$ are two i.i.d. exponential random variable with equal parameter σ^2. Moreover, $\min(|h_{SB}|^2,|h_{BD}|^2)$ is the maximum value in a set of (m-1) exponential random variables. We now use Lemma 2 in [6] and the fact that $\sqrt{SNR^{r-2}\left(SNR^r + 1\right)} \to SNR^{r-1}$ as $SNR \to +\infty$. So, we have

$$\lim_{SNR\to+\infty} \frac{\log\left\{\Pr\left[\min\left(|h_{SB}|^2, |h_{BD}|^2\right) \le SNR^{r-1} + \sqrt{SNR^{r-2}\left(SNR^r + 1\right)}\right]\right\}}{\log SNR} = (m-1)(r-1) \quad (7)$$

Now, with (6) and (7), we have that

$$\lim_{SNR\to+\infty} -\frac{\log p_{BRIAF}^{out}(SNR,r)}{\log SNR} = m(1-r) \quad (8)$$

Hence, the diversity curve $d(r)$, i.e. the DMT of the BRIAF protocol is $d(r) = m(1-r)$. When (m-1) potential relay terminals are involved, the BRIAF protocol achieves the optimal DMT curve (see Fig. 4) reaching the two extremes points $d^*(0) = m$ and $d^*(1) = 0$.

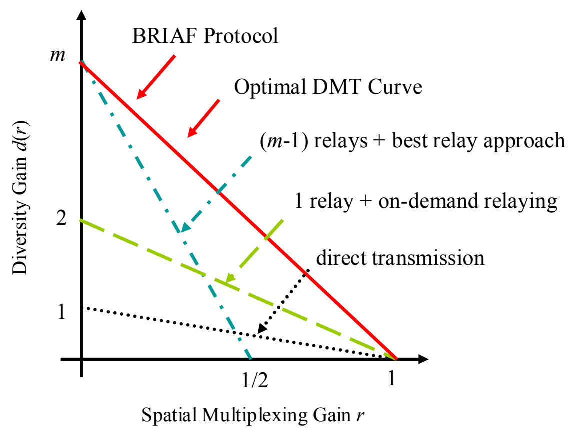

Fig. 4. Diversity-multiplexing trade-off curves for the BRIAF protocol and other cooperative and noncooperative schemes.

We end up this analysis with a last remark. The DMT analysis has been made considering a spectral efficiency R. We must note that the effective spectral efficiency is rather $\overline{R}$,

$$\overline{R} = R\,\Pr[I_D > R] + \frac{R}{2}\Pr[I_D < R] \tag{9}$$

Equation (9) follows the fact that the protocol operates at spectral efficiency R when the direct transmission is successful, and operates at spectral efficiency $R/2$ when a cooperative transmission is needed. Using the definition of I_D, we have that

$$\overline{R} = \frac{R}{2}\left[1 + \exp\left(-\frac{1}{\sigma^2}\frac{2^R - 1}{SNR}\right)\right] \tag{10}$$

Note that DMT curves cannot report the expected rate of (10) because the multiplexing gain r only reports that the data rate scales like R, without giving a precise value.

IV. SIMULATION RESULTS

We compare the performance of four transmission schemes: direct transmission, on-demand AF relaying with one relay [2], AF relaying with selection of the best relay terminal [6], and the BRIAF protocol. We assume slow fading Rayleigh channels between each pair of terminals, with equal variance: σ^2=1. The channels gains are assumed to be known at the receiver side. When the AF best relay approach and the BRIAF protocol are compared, they use the same number of relay candidates (m-1). The performance of the transmission schemes are given in terms of outage probability. Fig. 5 shows simulated performance results of the various transmission protocols. As the result in (8) and Fig.5 indicate, the BRIAF protocol and the AF relaying with the selection of the best relay terminal, achieve full spatial diversity of order m, the number of cooperative terminals, for sufficiently large SNR. Moreover, the BRIAF protocol achieves a better outage probability than the best relay approach because their respective expression are the following: $\Pr[I_{AF}<R]$ and $\Pr[I_{AF}<R/2]$. Note that the BRIAF protocol uses less resource than the AF relaying with selection of the best relay terminal because it implements on-demand cooperation.

V. CONCLUSION

In this paper, a new cooperative protocol, called the BRIAF protocol, has been presented. This protocol is based on the IEEE 802.11 standard for wireless networks and exhibits the following features: on-demand cooperation and selection of the best relay terminal. Cooperation will be activated only when the destination terminal fails in decoding the data transmitted by the source terminal. Besides, when a cooperative communication is necessary, only the best relay terminal participates in the communication. This twofold approach allows the optimization of the DMT curve. Moreover, two steps are involved in the relay selection process. The first step selects the relay candidates that can improve the direct transmission while the second step evaluates each relay candidate, and chooses the one that exhibits the best end-to-end channel gain. This approach allows resource savings at the relay candidates because only relevant candidates are pre-selected.

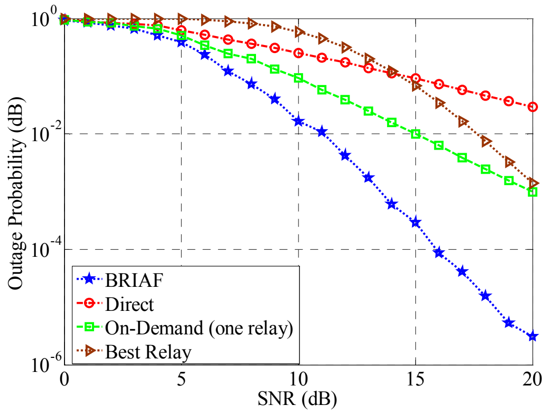

Fig. 5. Outage performance of noncooperative and cooperative transmission (m=4).

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